PETROGRAPHY OF IGNEOUS AND SEDIMENTARY ROCKS FROM THE THREE KINGS ISLANDS, NORTHERN NEW ZEALAND

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Abstract. The igneous rocks described are spilite, olivine basalt, basaltic tuff, and keratophyre intruded by numerous dikes and sills of basaltic composition. Almost all keratophyres are shown to be hydrothermally altered rhyolitic tuffs and ash flows that have undergone potassium metasomatism. The spilites are also products of sodium metasomatism of original olivine basalt. The alteration to keratophyres and spilites was favoured by high permeability and porosity in the rhyolitic tuffs and highly vesicular and brecciated basalts.

Suggested correlation is with the Whangakea Volcanics of North Cape. Sedimentary rocks are iron-stained conglomerate, clay and chlorite cemented arenite, siltstone, and calcareous argillite. It is concluded that the Three Kings Islands were a group of Cretaceous volcanic islands or seamounts, with initial submarine, but later subaerial volcanism.

Previously published petrographic descriptions of Three Kings Islands rocks by Bartrum (1936a, b) and Battey (1955, 1956) dealt only with the igneous rocks. They described spilite, keratophyre, and a rock that Bartrum described as an "albite porphyry", but which re-examination shows to be a basic tuff. Five chemical analyses were published in four different papers; these are given here (Table 1) for convenient reference. In the present work, Bartrum's original analysed rocks (P23641, 23642, 23643) have been re-examined, and a further 27 igneous and 7 sedimentary rocks (collected by B.W. Hayward and P.R. Moore in 1983) are described. P numbers refer to samples in the petrological collection of New Zealand Geological Survey, Lower Hutt. The geology of the Three Kings Is is described in the preceding paper (Hayward & Moore 1987) which gives details of localities and features mentioned here.

IGNEOUS PETROGRAPHY (THREE KINGS VOLCANICS)

Spilite

By far the most abundant rock type on the Three Kings Is is a fine-grained, microporphyritic spilite, which is sometimes found as pillow lavas (P44136), but more commonly as massive flows (P44117, 44118, 44125, 44129, 44134, 44137 and 44141).

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Table 1. Five chemical analyses* of Three Kings Islands rocks.

Weight %	1	2	3	4	5
SiO_2	75.10†	63.58	59.94	70.26	54.87
TiO_2	0.22	0.99	2.54	0.68	2.02
Al_2O_3	12.84	13.42	12.81	12.58	14.98
Fe_2O_3	0.70	2.10	3.76	3.30	1.65
FeO	1.36	5.67	9.29	2.00	8.89
MgO	0.30	1.37	3.65	0.36	3.33
CaO	0.32	2.75	6.22	1.26	4.06
Na_2O	5.12	4.31	5.25	4.77	5.73
K_2O	2.39	2.93	0.18	2.88	1.13
H_2O+	0.95	1.85	2.33	0.97	2.39
H_2O-	0.27	0.30	0.21	0.27	0.25
P_2O_5	0.04	0.35	0.36	0.52	0.47
CO_2	0.03	0.03	—	—	—
ZrO_2	0.01	0.01	—	—	—
S	0.06	0.02	0.12	—	—
Cl‡	0.02	trace	0.02	—	—
MnO	0.04	0.14	0.21	trace	0.04
NiO	—	0.01	0.02	—	—
BaO	0.05	0.05	trace	—	—
SrO	trace	0.01	—	—	—
Total	99.82	99.89	99.91	99.85	99.81

*1. Keratophyre, Great I, Three Kings Is (Bartrum 1936a, b).
2. Albitic porphyry (tuff), Great I, Three Kings Is (Bartrum 1936a, b).
3. Spilite, Great King I, Three Kings Is (Bartrum 1936a, b).
4. Dark-coloured keratophyre, summit of South West I, Three Kings Is (Battey 1955).
5. Spilite, cascade upper Tasman Stream, Great I, Three Kings Is (Battey 1956).

Analyst: Nos. 1-3 F.T. Seelye, 4&5 M.H. Battey.

† Weight %.
‡ Chlorine is almost certainly due to sea spray.

Many of the massive lavas are amygdaloidal, with amygdales infilled by quartz, calcite, chlorite, albite, and, rarely by K-feldspar or zeolites (P44125, 44129, 44130, 44134). The rocks are cut by veins of calcite and quartz or quartz and epidote; the latter may be up to 0.5 m in width (P44128).

Massive spilite is a dark grey, microporphyritic rock. Small, scarce phenocrysts of albite (An_{5-7}) and colourless augite are set in a microcrystalline groundmass of tiny, elongated laths of albite with abundant chlorite, granular epidote, magnetite, calcite and usually a little quartz. Apatite and sphene are constant accessories, and zircon occurs rarely. Texture is normally intersertal, but variolitic texture is well-developed in a few rocks (P44118, 44132) with spherules of radiating, fibrous albite containing tiny crystals of albite, epidote and magnetite at the centre. The albite phenocrysts range from less than 1 mm to over 3 mm in length and can be almost water-clear with fine albite twinning (P44122, 44137), or clouded by alteration products chlorite, epidote and sericite (P44117, 44125) and frequently twinned on the Carlsbad law. Highly altered feldspar phenocrysts tend to occur in amygdaloidal rocks, and may be partly replaced by K-feldspar (P44118, 44125, 44129). Pyroxene phenocrysts are nearly always completely unaltered, even when the feldspar is quite indeterminable (P44117); the pyroxene is a colourless, or very faintly pink or brown augite.

Although the groundmass is usually holocrystalline, but very fine-grained, a few samples have a groundmass of partly devitrified glass containing highly acicular, feathery crystals of clinopyrozene and abundant skeletal magnetite (P44117, 44118). A variant of the microporphyritic spilites is a fine-grained, equigranular rock with intersertal texture (P44134) composed of elongated laths of albite and curved crystals of a brown and rather fibrous diopsidic augite. Interstices are filled with granular augite, chlorite, epidote, albite and magnetite. The rock is quite vesicular and vesicles are infilled by radiating aggregates of bright green and slightly pleochroic (green-gold) chlorite. Bartrum's analysed sample (Bartrum, 1936a, b, Table 1, No. 1) is a rock of this type and contains the rare mineral babingtonite (Battey 1954). This mineral is present in very small amounts in P44134.

Quartz is a constituent in vesicles of nearly all amygaloidal spilites and may also be present in significant amounts in the groundmass (P44125). In these rocks, K-feldspar partly replaces albite and pervades the groundmass adjacent to veins and vesicles.

Keratophyre

These rocks are light-coloured, grey or greenish-grey and sometimes iron-stained. Often amygdaloidal, they are interbedded with amygdaloidal spilite in at least two main layers on Great I. In the field, some of the keratophyres (P44135) are quite obviously breccias, whereas others (P44124, 44147) show what appears to be flow banding. Both Bartrum (1936b) and Battey (1955) had difficulty in deciding between a flow or pyroclastic origin for the Three Kings keratophyres, and Battey (op. cit.) noted the similarity of some of the rocks to ignimbrite. For the present study, large thin sections were used in order to get a better idea of the texture. In all but one case (P44147), the rocks are clearly of pyroclastic origin, either ignimbrites or ash showers, although some may be redeposited water laid tuffs. Although all the rocks contain abundant groundmass and amygdaloidal quartz, there is no phenocrystic quartz so that the term "quartz keratophyre" is not used (cf. Battey 1955).

Typical keratophyres (P44147, 44116, 44119, 44124) contain sparse phenocrysts of albite (An_7) sometimes bent or shattered and occasionally (P44116) forming aggregates, set in a microcrystalline groundmass of tiny albite laths, often bent and irregular in shape, with quartz, flakes of yellow-green chlorite, abundant granular epidote and scarce magnetite. Staining with sodium cobaltinitrite showed only slight replacement of plagioclase phenocrysts by K-feldspar, but in the more vesicular rocks (P44147, 44149, 44125) K-feldspar rims vugs and borders quartz veins. It is sporadically distributed in the groundmass near vugs and veins, but is not found in massive, non-vesicular keratophyre (P44146). Pyrite, sometimes in euhedra up to 1 mm is a scarce component; it is often altered to hematite which produces iron-staining in the rock (P44146). Vugs are infilled with feathery and comb-structured quartz with centres of calcite or chlorite and very occasionally albite or zeolite (gmelinite). Prehnite is sometimes plentiful in the groundmass and veins of keratophyre breccias (P44135). In rocks showing strong "flow banding" (P44124), the bands are defined by darker, chlorite-rich material. In thin section the chlorite can be seen to be replacing flattened lumps of pumice, and hydrothermal alternation of pumiceous glass to a chlorite of very similar optic properties has been described from Wairakei (Steiner 1977:p62). The "flow banding" appears to represent pumice-rich layers in a pyroclastic deposit, and the lumps of pumice themselves are randomly oriented in the layer. Some keratophyres (P44119) retain a shadowy vitroclastic texture with glass shards replaced by zeolite. Fragments of more basic tuff in P44116, 44124 and 44135, are very scarce components, and in P44116 there are a few fragments of siltstone. In one keratophyre (P44147) the albite phenocrysts are strongly oriented with long axes in the direction of "flow-banding", although lumps of randomly oriented, chloritised pumice are obvious in the darker beds; the feldspar orientation could be the result of ash flow.

Basalt (P44121)

This sample comes from a pillow lava (Hayward & Moore this volume Fig.8) forming the basal 70 m of the volcanic sequence on West Island. The basalt is a holocrystalline, fine-grained, non-vesicular rock composed largely of plagioclase feldspar (An_{57}) and augite. Augite forms about 30% of the rock and is accompanied by scarce phenocrysts of olivine, almost completely altered to talc and calcite. Magnetite is a plentiful accessory. The basalt shows little alteration overall; feldspar and augite are completely unaltered, and there is only a very little chlorite and epidote in interstices.

Dike rocks

Although basic dikes are seen to cut each other, and have been referred to an older and younger set, they are compositionally the same and in fact, the "younger" dikes may be more altered than the "older".

Basalt dikes

These are typically (P44143) dark-grey, fine-grained, microporphyritic rocks with small phenocrysts of plagioclase (An_{73-65}) and colourless augite in a holocrystalline, equigranular groundmass of plagioclase (An_{60}) and augite. There are rare pseudomorphs of montmorillonite-chlorite after olivine, a few small flakes of reddish-brown biotite, and plentiful magnetite. Larger feldspar phenocrysts are commonly altered to sericite and clinozoisite and there is a small amount of calcite in sparse vesicles and in the groundmass. Pyrite and rare chalcopyrite are also present. An unusual variant of the basalt dikes of South West I is P44120, a fine-grained holocrystalline rock which consists almost entirely of plagioclase (An_{73-65}) and magnetite. Texture is intersertal, grading to variolitic. There are scarce flakes of brown biotite, and chlorite closely associated with calcite forming large pseudomorphs after olivine. Calcite is also found in small amounts throughout the rock. Tiny crystals of apatite are abundant, while strongly resorbed brown hornblende and highly chloritised pyroxene are scarce. Small patches of quartz are present in the groundmass.

Altered and spilitised basaltic dikes and sills

Most dikes show some degree of alteration. The least altered (P44126), from a 2 m thick dike on Tutanekai Rock, is a dark grey holocrystalline rock composed of small, scarce phenocrysts of augite rimmed by pink titan augite, in a groundmass of small augite crystals and laths of highly altered plagioclase. The plagioclase is diffusely zoned (An_{55-28}) with more calcic cores altered to sericite, chlorite, epidote and analcime. Interstitial chlorite is abundant, and there are rare chlorite and calcite pseudomorphs after olivine. Water clear albite forms small crystals and pools in the groundmass, and magnetite and pyrite are common accessories. A 4 m thick dike (P44127) cutting the one just described is slightly more altered and feldspar is completely albitised. Pyroxene phenocrysts and olivine psudomorphs are slightly larger and more abundant but otherwise the mineralogy and texture is very similar to the earlier dike. Staining revealed quite extensive replacement of albite phenocrysts by K-feldspar, but no alteration of the groundmass feldspar. Magnetite, pyrite and scarce chalcopyrite are also present. A sill (P44142) cutting spilite on South West I is very similar, but has phenocrysts of augite up to 10 mm in length.

A basic dike (P44140) cutting keratophyre on North East I is a highly porphyritic rock with altered feldspar phenocrysts up to 5 mm in length replaced by a mixture of sericite, epidote, analcime and chlorite. The original form of the crystals is sharply preserved against the groundmass of equigranular augite, altered plagiocase, water-clear albite and chlorite, epidote and magnetite.

On Great I, dikes of variolitic spilite are common.

Basaltic tuffs

Tuff (P44133) forms a layer between two spilite flows on Rosemary Rock and a very similar rock (P44525) is found interlayered with normal basalt pillow lava on West I. The tuffs are dark greenish grey rocks, mottled with irregular white patches of quartz and calcite, and bright green areas of chlorite and epidote. In thin section they are a highly brecciated, cryptocrystalline aggregate of chlorite, epidote, quartz, prehnite and zeolite (thomsonite), with fragments of basalt, spilite, dolerite, basaltic glass, and chloritised pumice. Amygdales are infilled with quartz and epidote, or occasionally with thomsonite. Glass shards replaced by prehnite give a vitroclastic texture to some areas of the rock. Staining reveals scarce K-feldspar in veins and patches, The "albite porphyry" described by Bartrum (1938b) appears on re-examination to be a basaltic tuff rather than a flow.

These rocks were interpreted as hyaloclasite in the field, but closer examination shows that although fragments of glassy, vesicular basaltic material predominates, and make up 70% of the sample from Rosemary Rock, the presence of fragments of pumice, coarser-grained spilite and glass shards between the fragments shows that the rocks are tuffs. Random orientation of pumiceous and elongated rock fragments suggests an air fall or water laid origin rather than an ash flow. The comparatively rare mineral babingtonite, described by Battey (1954) from spilite on Great I is also present in the tuff (P44133).

SEDIMENTARY PETROGRAPHY (TOKERAU FORMATION)

Pebble conglomerate

This rock (P44146), found near Hapuka Point on Great I, is a dark coloured fine pebble conglomerate in which sub-rounded to well-rounded pebbles, averaging less than 1 cm in diameter, are set in a fine siltstone matrix. The pebbles are siltstone, sandstone, chert and minor keratophyre. The siltstone in pebbles is very fine-grained with abundant flakes of mica, randomly distributed throughout the rock, which is not schistose. The sandstone pebbles are a lithic arenite in which the rock fragments are of the same type as those found as pebbles. Pebbles of chert are very plentiful and are commonly fractured and crossed by veins of secondary quartz. Less plentiful are small, rather more angular pebbles of keratophyre, very similar to that now exposed higher in the sequence on Great I. The matrix is a very fine micaceous siltstone similar to that found as pebbles. All pebbles and mineral grains are coated by reddish-brown oxides. The sedimentary conglomerate pebbles are similar to rock types found in the Tokerau Formation, but in the sample examined there was no sign of basic igneous material.

Sandstone

The sandstones on Great I (P44123, 44131, 44139, 44144) and West I (P44145) are all medium to fine-grained, dark grey rocks. Narrow veins of calcite and quartz are common. In thin section, they are moderately sorted to well-sorted, clay and chlorite-cemented arenites, grading to lithic feldsarenites. Clay and silt size matrix, highly micaceous, make up less than 10% of the rock, except in shear zones and siltstone layers whiere it might comprise 40% of the rock. Quartz is by far the most abundant detrital mineral, and occurs as both angular and rounded individual grains, and as fragments of chert and quartzite. Detrital feldspar is next in abundance, with albite being the most common type and oligoclase, microcline, or microperthite present in most rocks. Epidote, sphene, magnetite, apatite, bleached brown biotite, muscovite and zircon are less common detritals. Rock fragments are, in order of abundance: fine-grained micaceous siltstone, fine-grained sandstone, chert, keratophyre, and spilite. The cement is a pale yellowish-green chlorite.

Siltstone

This is interbedded with sandstone in very finely bedded units on Great and West Is. Individual siltstone/sandstone bands may be only 2-3 mm thick and show fine current bedding (P44144), or slight contortion of the bedding, possibly due to penecontemporaneous slumping. The siltstone contains the same detrital minerals and rock fragments as the sandstone, but more grains are angular and the proportion of fine clay size material is higher. Iron oxides and other opaque black materials are distributed as thin flakes throughout the sandstone and siltstone, and tend to concentrate on boundaries between layers.

Argillite

Argillite interbedded with spilite and keratophyres on South West I (P44516) is a dense, black, extremely hard rock, S.G. = 2.68. Slightly fissile, it breaks with a rough conchoidal fracture and has been hornfelsed by the overlying lavas and numerous dikes. Original bedding is possibly represented by very narrow 1-2 mm quartz rich layers. In thin section the rock is highly calcareous, with small pools and flakes of calcite forming approximately 20% of the rock. The main detrital mineral is quartz, which is present as sub-grounded grains with very diffuse and indistinct borders resulting from solution of quartz due to the high calcite content and thermal metamorphism. Rare feldspar grains are albite, and there are no identifiable rock fragments. Pyrite and iron oxides are plentiful and pyrite occasionally replaces microfauna, although (unidentifiable) foraminifera are more usually replaced by quartz in this rock. The extremely fine-grained groundmass is composed of chlorite, calcite, and micaceous clay. Abundant black flakes of organic material or iron oxides may define original bedding.

Conclusion

The sedimentary rocks are quartzose, relatively well-sorted, and the detrital minerals and rock fragments could all have been locally derived. The rarity of basic igneous material suggests that basaltic volcanism commenced after deposition of the bulk of the Tokerau Formation, although the common presence of keratophyre in the sandstone and pebble conglomerate points to an earlier episode of rhyolitic volcanism.

DISCUSSION

Formation of spilite and keratophyre

The Three Kings provide an unusually clear example of the formation of spilite and keratophyre by hydrothermal metamorphism of basic lavas and acid tuffs, the controlling factor in the alteration being permeability and porosity of vesicular lavas and tuffs. This process is best demonstrated on West I where massive, non-vesicular pillow lavas (Hayward & Moore this volume Fig.8) which are normal basalts, are overlain by acid tuffs and amygdaloidal basic lavas now represented by keratophyre and spilite.

It is now generally recognised that spilites are the product of low grade zeolite or greenschist facies metamorphism, either regional or hydrothermal (Cann 1969; Coombs 1974), in type, and Leitch (1978), has described hydrothermal metamorphism leading to spilitisation of the Whangakea Basalt which forms part of the mainland nearest to the Three Kings Group. The mineralogy and texture of the basic lavas is similar except that the calcic plagioclase (An_{57}) of the basic pillow lava is replaced by albite in the overlying spilites, accompanied by a greater development of epidote – chlorite and epidote – quartz veins. In some partly spilitised dike rocks (e.g. P44126) the feldspar has cores of labradorite diffusely zoned to oligoclase at margins of phenocrysts, and albite has replaced the groundmass feldspar. Sodium metasomatism has been followed or accompanied by potassium metasomatism resulting in the partial replacement of albite phenocrysts and groundmass in more amygdaloidal spilites and keratophyres, and crystalisation of K-feldspar round vesicles and veins in more massive rocks. The K_20 content of spilites and keratophyres from Three Kings Is is generally lower than in similar rocks from the mainland (Battey 1955, 1956).

Hydrothermal spilitisation of the Three Kings rocks appears to be fairly localised, as underlying sandstones and siltstones show little alteration apart from slight development of secondary quartz around detrital grains and in narrow veins with calcite. Zeolites are found only locally in some of the spilites and keratophyres (P44125, P44129); mainly thomsonite or, rarely, gmelinite (P44129). Prehnite is abundant in veins and lenses in basic tuffs, and calcite is present in veins, amygdales and groundmass of nearly all rocks.

The type of alteration, the minerals formed, and the relationship between porosity and permeability of the rocks and the localization and extent of alteration, can be compared to hydrothermal alteration in present day geothermal fields such as Wairakei (Steiner 1977) and Broadlands (Browne & Ellis 1970).

Nature of the volcanism

Pillow lavas in the sequence show that some of the volcanism must have been submarine, and the scarcity and small size of vesicles in the basal pillow lava on West I suggests that this unit was erupted at a depth of at least 200 m (Moore 1965). However, overlying the pillow lavas on West I are highly amygdaloidal spilites and keratophyre which is obviously an altered rhyolitic tuff of ash flow or air fall origin. The basaltic tuffs found on South West I and Rosemary Rock also point to shallow water, although material from ash flows and falls may be redeposited from higher levels on the flanks of island volcanoes and seamounts (Stanley & Taylor 1977).

It is probable that the Three Kings Is represent a group of Cretaceous volcanic islands or seamounts in which the initial volcanism was submarine, but continued activity rapidly built up the volcanic pile to near sea level. For short periods, activity may have been above sea level, allowing the eruption of rhyolitic ash flows. The scarcity of sediments between flows suggests that volcanism was either intense and short lived, or that later activity was partly sub-aerial.The co-existance of acid and basic volcanics is a worldwide phenomenon and has been well described from Iceland (Walker 1966) where rhyolitic flows and pyroclastic deposits make up about 10% of the Tertiary volcanic pile. In the Three Kings, keratophyre makes up far less than 10% of the sequence, but is significant on Great I and on West I. The volume involved here is not too great to preclude an origin by differentiation of a basalt magma, although a contribution from the quartzose and highly micaceous Tokerau Formation might be involved in the hydrothermal silicification and potassium enrichment of the rocks.

Correlation

The nearest volcanic rocks, the partially spilitised basalts of the Whangakea Volcanics in the Cape Reinga area, are petrologically extremely similar. Bartrum and Turner (1928) describe olivine bearing, basalt pillow lavas which are identical to those on West Island, and the spilites of the Whangakea Volcanics are also very similar. The submarine ridge between Cape Reinga and Three Kings is composed of basalt, including olivine basalt, and Summerhayes (1969) correlated these rocks with the Whangakeas. The presence of keratophyre on Three Kings, and its apparent absence in the Whangakea Volcanics, might favour a correlation with the Houhora Volcanics, which include keratophyres at Mt Camel and Doubtless Bay (Battey 1955). However, the Whangakea Volcanics include laccoliths or sills (F Brook pers. comm. 1985) of "granophyre" containing up to 40% modal quartz (Bennett 1976), and it is interesting to note that Bartrum (1929) described the Mt Camel keratophyres as "albitic granophyre". It may be that the Whangakea intrusions are feeding channels for acidic volcanism, not at present exposed in the North Cape area. The Houhora Volcanics do not contain olivine and the degree of alteration shown by the spilites of the Houhora Volcanics is greater; no unspilitised basalt has been reported, although alteration may depend on the distance from a heat source. The mafic-ultramafic pluton at North Cape is an obvious source, but further south, near Ngataki and Cape Karikari, there are significant positive Bouger anomalies indicating further centres of mafic intrusion. Mt Camel and Doubtless Bay would be very much nearer these centres than would Three Kings or Cape Reinga and it is significant that the basalts of the Cape Reinga volcanics are not spilitised whereas those further east are (Leitch 1978). More permeable rocks on the Three Kings are spilitised and K-metasomatised, but non-amygdaloidal rocks are unaltered, and it is probable that a centre closer than North Cape was the focus for the Three Kings volcanism.

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